Stopping Powers of Be, Al, Ti, V, Fe, Co, Ni, Cu, Mo, Rh, Ag, Ta, and Au for 28.8 MeV Alpha Particles

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Bull. Inst. Chem. Res., Kyoto Univ., Vol. 55, No. 1, 1977

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Received January 31, 1977

Stopping powers of Be, Al, Ti, V, Fe, Co, Ni, Cu, Mo, Rh, Ag, Ta, and Au for 28.8 MeV alpha particles have been measured with a silicon detector and associated electronic equipment. It has been confirmed that the stopping power for alpha particles devided by 4 is higher than that for protons of the same velocity. The deviations are from 2.4 to 4 percent.

I. INTRODUCTION

It was first found experimentally by Andersen *et al.*[1] that one fourth of the stopping power for alpha particles is slightly larger than the stopping power for protons of the same velocity. And this effect was experimentally confirmed by our previous experiment.[2]

Presently, this effect has been explained as the effect of higher Born approximation and called Z_1^3 effect,[3~6] where Z_1 is the atomic number of the particles. These theories of Z_1^3 effect agrees fairly well with the experiment of Andersen *et al.*[1]

In a recent letter,[7] we have reported that our recent measurements of stopping powers of various metallic elements for 28.8 MeV alpha particles do not agree with the theories and the differences between the stopping powers for alpha particles and for protons are larger than those predicted by the theories.

Although there remains yet a question[8,9] whether our proton data are too low or the proton data of Andersen *et al.*[10~13] are too high, we want to report here the details of our new experiments and the full data on 28.8 MeV alpha particles.

II. EXPERIMENTAL PROCEDURE

The alpha particles accelerated with the Kyoto University Cyclotron were used for the present experiment. The method to measure the energy loss of alpha particles in sample foils is quite the same as described in detail in the previous papers.[14,15]

Figure 1 shows the experimental setup. The absolute value of the incident alpha particle energy was determined by the analyzing magnet. The effective radius of curveture of the alpha particle paths in the analyzing magnet has been determined in the previous experiment.[15] The very same value was used in the present experiment. Therefore, the energy scale of the present measurements is based on the same energy calibration as the previous measurements for protons.[15]

The beam scattered at an angle of 15 degrees by a gold scatterer of 180 μg/cm^2 was used for the measurement. The sample foil was fitted to one of the two windows

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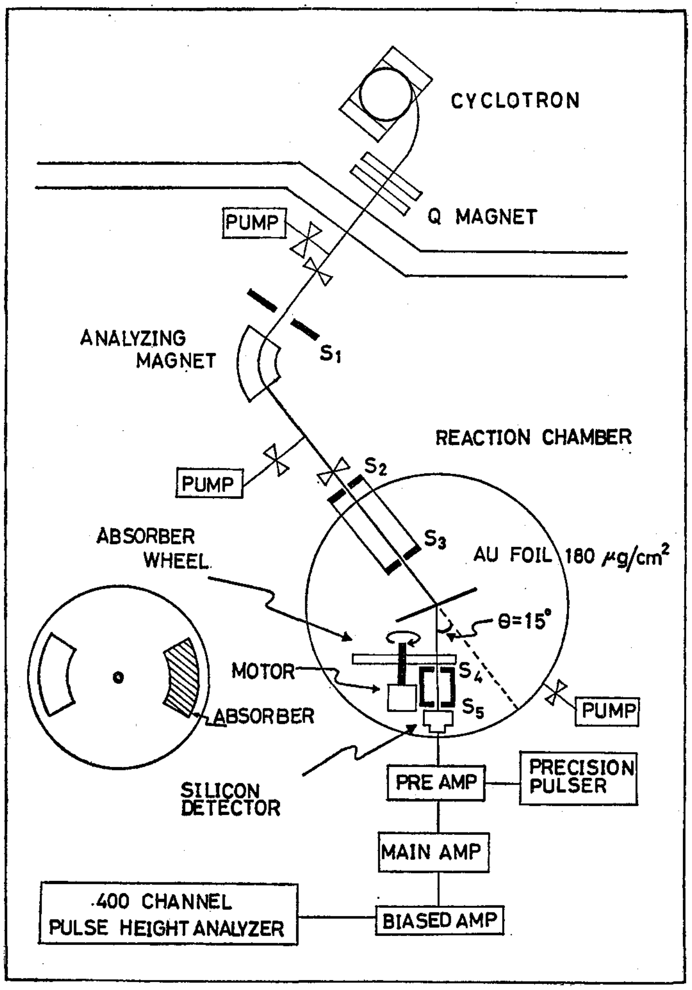


Fig. 1 Experimental setup for the energy loss measurement.

of the absorber wheel and the wheel was rotated in front of a silicon detector (ORTEC). Thus, the pulse heights with and without the sample foil were measured simultaneously in one exposure. The double slit system consists of S_4 and S_5, which have circular apertures of 1.5 mm and 2.0 mm in diameter and are placed 80 mm apart. This device was set between the absorber wheel and the detector to limit the direction of the alpha particles incident on the detector.

The pulses from the detector were amplified with a low noise amplifier and the relevant portion of the pulse height spectrum was expanded by a biased amplifier. The output of the biased amplifier was fed into a 400-channel pulse height analyzer.

The energy calibration of the expanded pulse height spectrum was performed by measuring the alpha particles elastically scattered by an aluminium target of 1.692 mg/cm² at various angles and was crosschecked by a precision pulser.

The measurements were made four times for each element and the average values were obtained.

The sample foils used are as follows:

Beryllium

Thickness: 2.4301±0.0063 mg/cm². Stated purity: unknown but presumed to be 99 percent or up. Supplier: Brush Beryllium Co. The very same foil as used in the previous experiment.[2)]

Aluminium

Thickness: 4.9374±0.0074 mg/cm². Stated purity: 99.8 percent. Supplier: Toyo Aluminium Co., Ltd.

Titanium

Thickness: 6.1547±0.0092 mg/cm². Stated purity: 99.5 percent (0.25 percent Fe). Supplier: A. D. Mackay, Inc.

Vanadium

Thickness: 7.6299±0.0114 mg/cm². Stated purity: 99.9 percent. Supplier: A.D. Mackay, Inc.

Iron

Thickness: 6.1285±0.0092 mg/cm². Stated purity: 99.9 percent. Supplier: Fukuda Metal Foil and Powder MFG Co., Ltd.

Cobalt

Thickness: 9.1884±0.0138 mg/cm². Stated purity: 99.9 percent. Supplier: A.D. Mackay, Inc.

Nickel

Thickness: 6.7205±0.0101 mg/cm². Stated purity: 99.9 percent. Supplier: Fukuda Metal Foil and Powder MFG Co., Ltd.

Copper

Thickness: 7.4178±0.0111 mg/cm². Stated purity: 99.9 percent. Supplier: Fukuda Metal Foil and Powder MFG Co., Ltd.

Molybdenum

Thickness: 6.8050±0.0102 mg/cm². Stated purity: 99.95 percent. Supplier: A.D. Mackay, Inc. The very same foil as used in the previous experiment.[2)]

Rhodium

Thickness: 7.7488±0.0116 mg/cm². Stated purity: 99.9 percent. Supplier: A.D. Mackay, Inc.

Silver

Thickness: 8.9613±0.0134 mg/cm². Stated purity: 99.9 percent. Supplier: Fukuda Metal Foil and Powder MFG Co., Ltd.

Tantalum

Thickness: 10.3447±0.0155 mg/cm². Stated purity: 99.9 percent. Supplier: A.D. Mackay, Inc. The very same foil as used in the previous experiment.[2)]

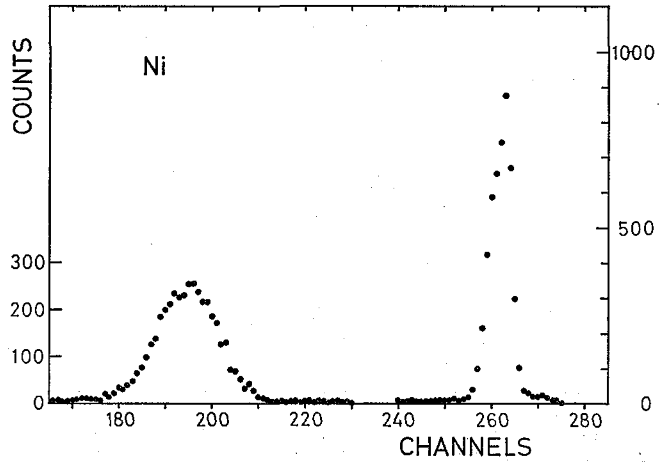
Gold

Thickness: 10.5060±0.0158 mg/cm². Stated purity: 99.95 percent. Supplier: Ishifuku Metal Industry Co., Ltd. The very same foil as used in the previous experiment.[2)]

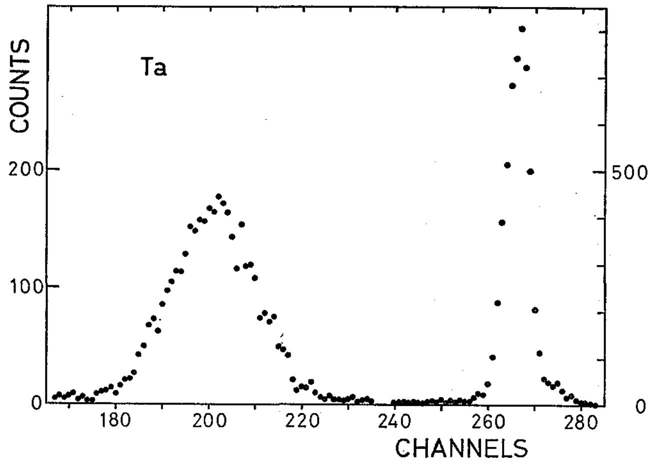
III. RESULTS

The typical pulse height spectra are shown in Fig. 2. The numerical results of the pulse height measurements for Al, Ag, and Au are shown in Table I as examples.

From the measurement of the elastically scattered alpha particles by the aluminium target at different angles, the energy scale of the pulse height spectra was determined as 14.7857 ± 0.0605 keV/channel.



(a) Ni



(b) Ta

Fig. 2 Typical pulse height spectra.

Table II lists the results. In the table, Δt is the thickness of the foil, ΔE is the energy loss of alpha particles in the sample foil. The symbol $\bar{E}$ denotes the average energy defined as

$$\bar{E} = E_0 - \Delta E/2 ,$$

Table I. Examples of Numerical Results of Pulse Height Measurements. P.E. Denotes the Propagation Error and S.E. Denotes the Standerd Error

	Element and Run	No Absorber Peak (channel)	Absorber Peak (channel)	Pulse Height Difference (channel)
Al	Run 1	262.267±0.034	203.190±0.047	59.078±0.058
	Run 2	262.650±0.036	203.572±0.053	59.078±0.064
	Run 3	262.823±0.043	203.845±0.063	58.978±0.076
	Run 4	262.221±0.037	203.131±0.054	59.090±0.066
	Average	262.490±0.019 (P.E.)		59.056±0.033 (P.E.)
		±0.147 (S.E.)		±0.026 (S.E.)
Ag	Run 1	263.723±0.042	192.280±0.087	71.443±0.096
	Run 2	263.673±0.043	192.149±0.090	71.524±0.100
	Run 3	263.973±0.040	192.567±0.087	71.406±0.096
	Run 4	263.429±0.040	191.841±0.087	71.588±0.095
	Average	263.699±0.021 (P.E.)		71.490±0.049 (P.E.)
		±0.112 (S.E.)		±0.051 (S.E.)
Au	Run 1	262.247±0.041	197.408±0.112	64.840±0.119
	Run 2	262.419±0.042	197.520±0.111	64.899±0.119
	Run 3	263.279±0.041	198.734±0.115	64.545±0.122
	Run 4	263.056±0.039	198.185±0.114	64.871±0.120
	Average	262.750±0.020 (P.E.)		64.789±0.060 (P.E.)
		±0.248 (S.E.)		±0.079 (S.E.)

Table II. Results. The Incident energy is 28.7552±0.0177 MeV.

Element	Δt (mg/cm^2)	ΔE (keV)	$\bar{E}$	$\bar{E}'$	$\Delta E/\Delta t$ (keV/mg cm^{-2})
Be	2.4301	477.4	28.5165	7.1783	196.45
	±0.0063	±2.1	±0.0177		±1.00
Al	4.9374	873.2	28.3186	7.1285	176.85
	±0.0074	±3.6	±0.0178		±0.85
Ti	6.1547	943.8	28.2833	7.1196	153.35
	±0.0092	±3.9	±0.0178		±0.74
V	7.6299	1136.5	28.1870	7.0954	148.95
	±0.0114	±4.7	±0.0178		±0.72
Fe	6.1285	902.4	28.3040	7.1248	147.25
	±0.0092	±3.7	±0.0178		±0.71
Co	9.1884	1333.6	28.0884	7.0705	145.14
	±0.0138	±5.5	±0.0179		±0.70
Ni	6.7205	993.8	28.2583	7.1133	147.88
	±0.0101	±4.1	±0.0178		±0.72
Cu	7.4178	1033.7	28.2384	7.1083	139.35
	±0.0111	±4.3	±0.0178		±0.67
Mo	6.8050	833.9	28.3383	7.1334	122.54
	±0.0102	±3.5	±0.0177		±0.60
Rh	7.7488	914.0	28.2983	7.1234	117.95
	±0.0116	±3.8	±0.0178		±0.57
Ag	8.9613	1057.0	28.2267	7.1054	117.95
	±0.0134	±4.4	±0.0178		±0.57
Ta	10.3447	963.1	28.2737	7.1772	93.10
	±0.0155	±4.4	±0.0178		±0.49
Au	10.5060	957.9	28.2763	7.1178	91.18
	±0.0158	±4.1	±0.0178		±0.45

where E_0 is the incident alpha particle energy. The symbol $\bar{E}'$ denotes the energy of protons which have the same velocity as alpha particles of energy $\bar{E}$. The ratio $\Delta E/\Delta t$ corresponds in a good approximation to the stopping power, $-dE/dt$, at the average energy $\bar{E}$.

Since in the present experiment only alpha particles which passed through the double slit system S_4 and S_5 were detected by the silicon detector, the actual path length of alpha particles in the foil was assumed to be equal to the foil thickness and no correction was made for the multiple scattering. The systematic error caused by this approximation is at most 0.05 percent.

Further, since in the present experimental setup the alpha particle beam does not scan all over the sample foil, an additional error of 0.2 percent has been added to the stopping power values. This additional error stands for the possible nonuniformity of the sample foil.

The effect of the geometry in the energy loss measurement has been investigated earlier.[16] It has been confirmed that the goodness of the geometry does not affect the energy loss measurement for the degree of goodness of the geometry in the present experiment.

IV. DISCUSSION

1. Comparison of Present Results with Previous Results

In Table III, the comparison of the present results with the previous results[2] for common elements are shown.

Table III. Comparison with the Previous Alpha Data. All values have been devided by 4 and reduced to 7.0 Mev.

Element	Present Data (keV/mg cm^{-2})	Previous Data* (keV/mg cm^{-2})	Difference (%)
Be	50.32±0.27	49.25±0.49	+2.13±1.11
Al	45.00±0.22	45.01±0.44	−0.02±1.09
Cu	35.36±0.17	35.03±0.33	+0.93±1.05
Mo	31.20±0.15	31.43±0.30	−0.74±1.09
Ta	23.65±0.12	23.69±0.23	−0.17±1.10
Au	23.17±0.11	22.85±0.22	+1.38±1.08

* ref. 2

All values have been devided by 4 and reduced to the proton energy of 7.0 MeV. The reduction of the stopping power value to 7.0 MeV was made by multipling $(\ln v^2/v^2)_{7.0}/(\ln v^2/v^2)$.

Only for Be the difference are barely significant. But for other elements the differences are not significant statistically. Taking account of the errors of the previous data (∼1 percent), the general agreement between the old and new data is satisfactory.

2. Comparison of Present Data with Our Proton Data

In Table IV, the comparison of the present data with our own proton data[14,15] are shown. The differences amount to from 2.5 to 4 precent.

Table IV. Comparison with our Proton Data. Present results have been devided by 4 and reduced to 7.0 MeV.

Element	$(dE/dx)_p^*$ (keV/mg cm^{-2})	$(dE/dx)_\alpha \times 1/4$ (keV/mg cm^{-2})	Difference (%)
Al	43.62±0.15	45.00±0.22	3.16±0.61
Ti	37.65±0.17	38.97±0.19	3.51±0.66
Fe	36.18±0.16	37.45±0.18	3.51±0.66
Ni	36.16±0.19	37.55±0.18	3.84±0.72
Cu	34.50±0.12	35.36±0.17	2.49±0.60
Mo	29.94±0.14	31.20±0.15	4.21±0.70
Ag	28.98±0.11	29.92±0.14	3.24±0.61
Ta	23.08±0.11	23.65±0.12	2.47±0.69
Au	22.26±0.09	23.17±0.11	4.09±0.64

* ref. 14, 15.

The comparisons with our proton data as well as with the Z_1^3 theory[4] have already been reported.[7] However, in the recent study[8] of the stopping powers of various elements for 6.75 MeV protons, it has been revealed that our previous data for protons[14,15] might be too low by some 1 percent. Consequently, the true differences might be some 1 percent samller than as shown in Table IV. Therefore, we want to withhold the discussion about the comparison of the present data with the the proton data until the correct stopping power data for protons are established.

3. Comparison of Present Data with Andersen's Data

For reference, in Table V the present results are compared with the data of Andersen *et al.*[10~13]

Table V. Comparison with Andersen's Data. The Present results have been devided by 4 and reduced to 7.0 MeV.

Element	$(\Delta E/\Delta t)_\alpha \times 1/4$ (keV/mg cm^{-2})	Andersen* (keV/mg cm^{-2})	Difference (%)
Be	50.32±0.27	50.34±0.15	−0.04±0.62
Al	45.00±0.22	44.81±0.13	+0.42±0.58
Ti	38.97±0.19	38.92±0.12	+0.13±0.56
V	37.73±0.18	37.80±0.11	−0.19±0.56
Fe	37.45±0.18	37.28±0.11	+0.45±0.56
Co	36.64±0.18	36.06±0.11	+1.58±0.57
Ni	37.55±0.18	37.29±0.11	+0.69±0.56
Cu	35.36±0.17	35.12±0.11	+0.68±0.57
Ag	29.92±0.14	29.48±0.09	+1.47±0.57
Ta	23.65±0.12	23.66±0.07	−0.04±0.59
Au	23.17±0.11	22.67±0.07	+2.16±0.56

* ref. 10∼13.

For most elements, the present results agree well with the data of Andersen *et al.* For Co, Ag, and Au, the differences are statistically significant.

Although not yet surely established, the data of Andersen *et al.* are considered to be slightly too high.[8] Therefore, Table V should be interpreted as showing slight differences between stopping powers for alpha particles and protons at the proton velocity of 7 MeV. Further discussion will be deferred until the correct stopping power data for protons are undoubtely established.

ACKNOWLEDGMENTS

The authors would like to thank Professor T. Yanabu for his encouragement and support throughout the work. Thanks are also due to Mr. K. Fujita and the members of the cyclotron crew of Kyoto University for their kind cooperation.

REFERENCES

(1) H. H. Andersen, H. Simonsen, and H. Sϕprensen, *Nuclear Phys.*, **A125**, 171 (1969).
(2) R. Ishiwari, N. Shiomi, S. Shirai, T. Ohata, and Y. Uemura, *Bull. Inst. Chem. Res., Kyoto Univ.*, **49**, 403 (1971).
(3) J. C. Ashley, R. H. Ritchie, and W. Brandt, *Phys. Rev.*, **B5**, 2393 (1972).
(4) J. D. Jackson and R. L. McCarthy, *Phys. Rev.*, **B6**, 4131 (1972).
(5) J. C. Ashley, R. H. Ritchie, and W. Brandt, *Phys. Rev.*, **A8**, 2402 (1973).
(6) J. C. Ashley, *Phys. Rev.*, **B9**, 334 (1974).
(7) R. Ishiwari, N. Shiomi, and S. Shirai, *Phys. Lett.*, **51A**, 53 (1975).
(8) Our new experiment. To be soon published elsewhere.
(9) H. H. Andersen, *Phys. lett.*, **56A**, 443 (1976).
(10) H. H. Andersen, C. C. Hanke, H. Sϕrensen, and P. Vajda, *Phys. Rev.*, **153**, 338 (1967).
(11) H. H. Andersen, C. C. Hanke, H. Simonsen, H. Sϕrensen, and P. Vajda, *Phys. Rev.*, **175**, 389 (1968).
(12) H. H. Andersen, H. Simonsen, H. Sϕrensen, and P. Vajda, *Phys. Rev.*, **186**, 372 (1969).
(13) H. Sϕrensen and H. H. Andersen, *Phys. Rev.*, **B8**, 1854 (1973).
(14) R. Ishiwari, N. Shiomi, S. Shirai, T. Ohata, and Y. Uemura, *Bull. Inst. Chem. Res., Kyoto Univ.*, **49**, 390 (1971).
(15) R. Ishiwari, N. Shiomi, S. Shirai, and Y. Uemura, *Bull. Inst. Chem. Res., Kyoto Univ.*, **52**, 19 (1974).
(16) R. Ishiwari, N. Shiomi, T. Katayama-Kinoshita, and F. Sawada-Yasue, *J. Phys. Soc. Japan*, **39**, 557 (1975).